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西天山温泉地区全新世沉积物元素地球化学记录及其古环境意义

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摘 要：通过对西天山温泉湿地钻孔沉积物Rb/Sr、Sr/Ca、Ti/Sr、Mg/Ca、Zr/Sr 5种特征元素比值综合分析与对比研究，识别温泉湿地全新世气候变化驱动模式。结果表明：(1) 温泉湿地沉积物提供了新疆全新世气候变化的可靠记录，其全新世气候经历了暖干(10300—7700 cal a BP)-暖干向温湿过渡期(7700—7000 cal a BP)-温湿(7000—4200 cal a BP)-温干(4200—2900 cal a BP)-冷湿(2900—81 cal a BP)5个阶段变化过程。(2) 与邻近区域其他替代性指标所指示的气候变化相吻合，验证了新疆地区全新世早期暖干、中晚期冷湿的气候变化模式，表明新疆地区全新世气候类似于西风模式。(3) 温泉湿地沉积物化学元素比值在7700—7000 cal a BP期间指示的降温过程是8200 cal a BP全球变冷事件的响应；4200—2900 cal a BP期间指示的升温过程或许与3000—2900 cal a BP敦德冰芯反映的全新世次高温事件相关。同时，与周边区域其他替代性指标对比发现，新疆地区逐渐湿润的变化趋势可能是全新世温度降低与降水增加共同作用的结果。

关 键 词：湿地；元素比值；全新世；气候环境；区域对比；新疆

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西风环流影响显著的新疆地区[1]，地处我国西北干旱区，因其生态环境体系脆弱和自然环境结构简单，对气候响应敏感，自然而然成为古气候学者们探讨区域气候演化模式的热点[2]。新疆全新世气候模式主要两种观点，即季风模式[3-4]和西风模式[5-6]。为进一步探讨西北地区(主要是新疆地区)气候演变模式，学者们以湖泊沉积物为研究载体，先后在艾比湖[7]、博斯腾湖[8-11]、玛纳斯湖[4,12-13]、巴里坤湖[14-15]、乌伦古湖[16-20]等区域开展古气候古环境研究工作并取得丰硕成果。

尽管已有相当一部分学者总结了西北地区全新世时期气候演化模式[21-25]，但依旧存有许多不同观点，尤其是全新世以来新疆地区的水热组合模式还存在较大分歧。为解决这些分歧，一些学者就西北地区气候演变及其机制开展相关研究，并尝试从不同角度揭示其变化机制[26-28]，如Wang等[26]认为新疆全新世湿度变化可能与北大西洋冬季温度有关；Zhang等[27]的研究表明，北疆全新世中晚期湿度的增加是温度降低与降水增加共同作用的结果；而Zhao等[28]则认为，中亚地区8 ka出现的升温与区域湿度增加有关，可能是Laurentide冰盖和其他高纬度冰盖影响大气环流所致。这些争议和差异要求更多来自新疆地区的高分辨率气候记录，以进行更深入的古气候重建，这将对理解西风区古气候环境演化产生重大意义[1]。

沉积物中元素组合因元素性质、沉积环境不同而千差万别，可用于揭示沉积物物源、控制因素及其沉积环境，是研究环境演变的重要替代指标之一。干旱条件下的沼泽湿地多发育于负地貌中[29]，低洼地势有利于化学元素富集，因此可通过湿地沉

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积物化学元素的时空分布反映其发育过程与区域环境演变[30]。目前，利用化学元素反演古气候在我国湿地沉积物中已有相当广泛应用[30-34]，充分表明某些特征化学元素比值有潜力反演湿地古气候演变过程。

本文基于新疆温泉湿地沉积物地球化学元素比值分析，旨在重建10300 cal a BP以来中国新疆地区的环境和气候变化，通过区域对比验证新疆地区水热组合，促进对西北地区全新世气候模式的认识和了解。

1　研究区概况

研究区域为博尔塔拉河国家湿地公园(44°58′~45°12′N，80°53′~81°39′E)，位于新疆温泉县(图1)。天山山区是新疆降水最充沛区域[46]，西天山的温泉县因地形所限，降水较少，属大陆性中温带干旱半干旱气候，主要受中纬度西风环流控制[47]，四季不分明，冬季漫长不严寒，夏季短暂不炎热[48]。博尔塔拉河和鄂托克赛河是县境内两条主要河流，以降水和冰川融水补给。草原植被主要分布在海拔1200~2400 m处，山地及山间盆地和谷地降雨量相对稀少，草原植被覆盖度低于65%[48]。根据温泉气象站资料，温泉县气温低，湿度大，蒸发量小[49]，其多年平均降水量为223.5 mm，最大年降水量为394.3 mm，最小年降水量为77.8 mm，多年年均气温为3.7 ℃，多年平均年蒸发量为1540.3 mm，干旱指数为3.9[47]。

2　材料和方法

2017年9月，使用内径5 cm的半管泥炭岩芯取样器从温泉湿地中心(44°58′N，80°01′E，海拔1300 m)提取长126.75 cm的沉积序列(WQ-1)[50]，并以0.25~1 cm间距在WQ-1中取样，分割后样品装入已标记聚乙烯塑封袋保存，最终得到89个样品(干重1~2 g·样$^{-1}$)。顶部至50.25 cm处，因含水量高且泥炭层松散压实而未完全恢复，将以下长约76.5 cm部分用于本次研究。钻孔岩芯由上部的棕黑色泥炭(长34.75 cm)和下部的黑灰色粉土(长41.75 cm)两部分组成[50](图2a)。8个样品用于^{14}C测年[50]，并基于Bacon包建立年龄-深度模型[51](图2b)。实验室

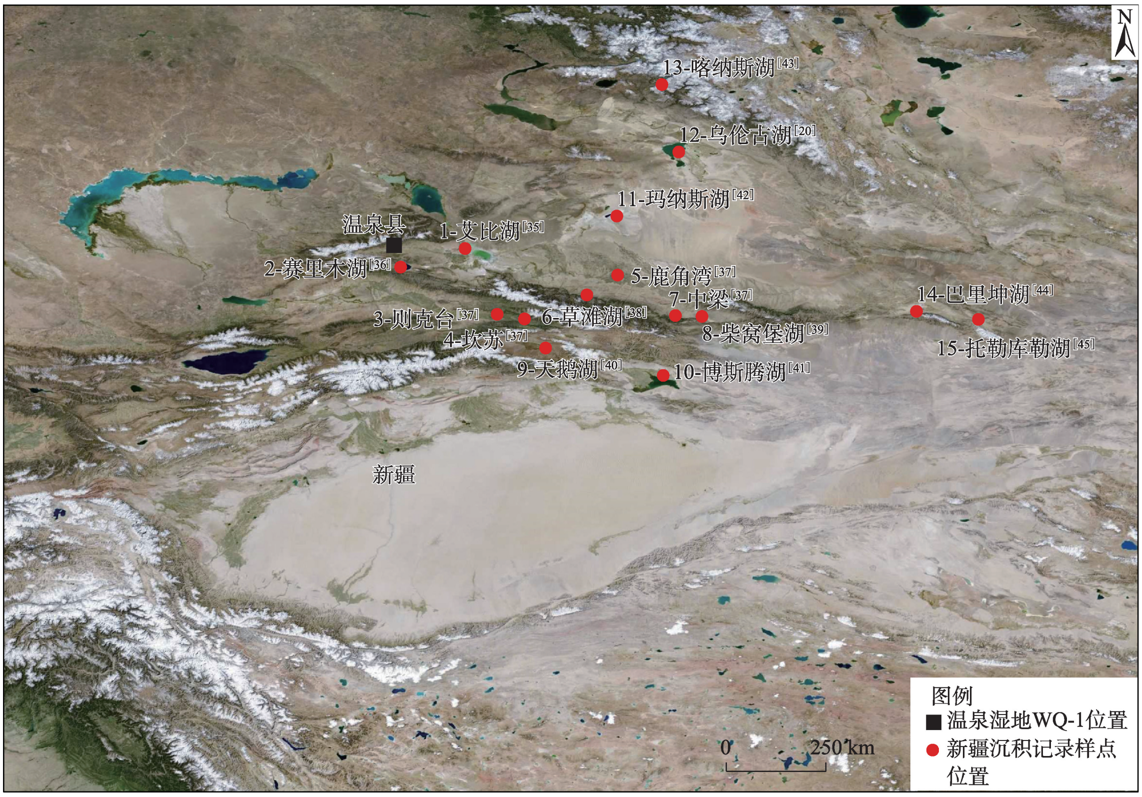


图1　新疆地区沉积物代用指标记录全新世湿度变化

Fig. 1　Holocene humidity changes recorded by the sediment proxy index in Xinjiang

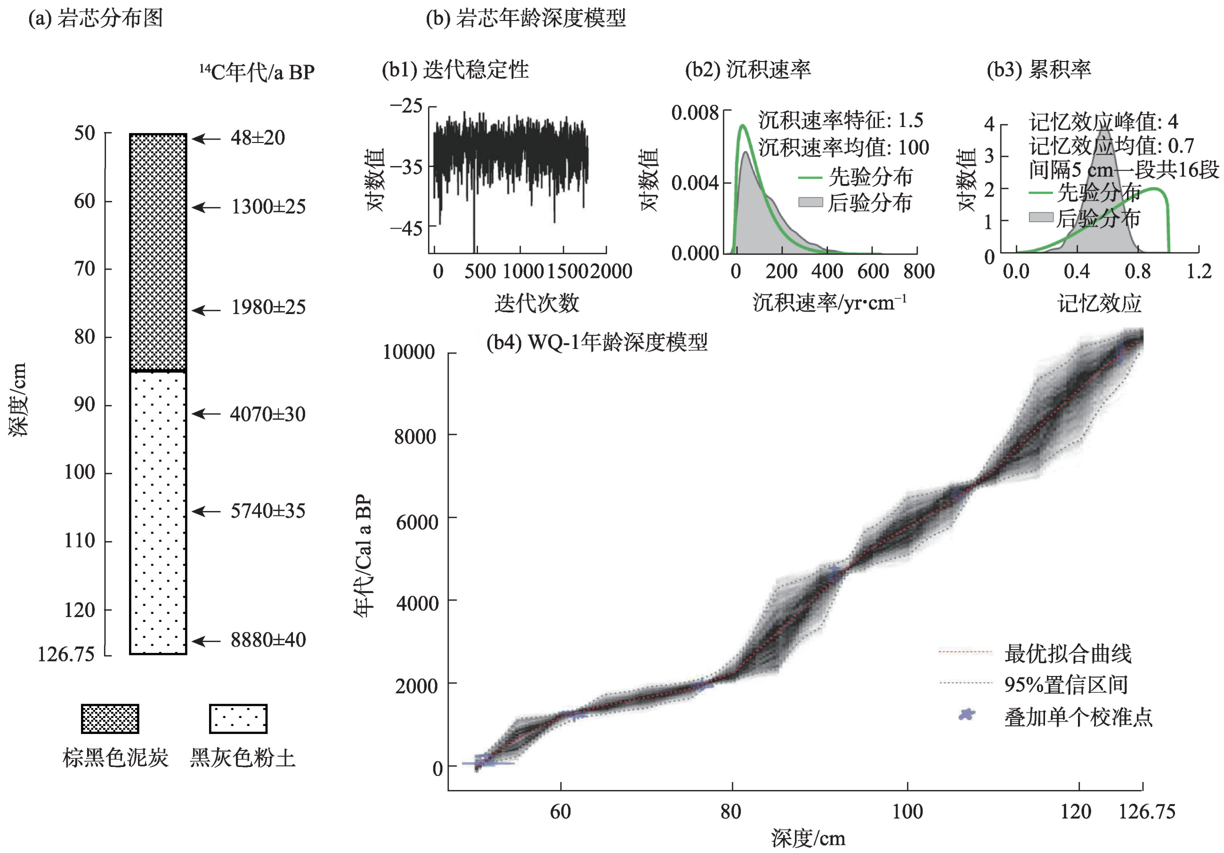


图2 温泉湿地WQ-1岩芯年代深度模型图[50]

Fig. 2 WQ-1 core age depth model of Wenquan wetland[50]

内将89个样品研磨至200目，然后以105 ℃恒温烘干，取0.120~0.125 g样品硝化，利用美国电感耦合等离子体原子发射光谱仪(Leeman Labs Profile ICP-AES)测定Rb、Ti、Sr、Zr、Mg、Ca 6种元素浓度，平行分析误差小于±5%[52-53]。实验于2019年5月，在澳实矿物实验室进行。

3 结果与分析

3.1 地球化学元素比值的环境指示意义

在表生地球化学过程中，Rb弱迁移而残留于风化壳内，Sr易迁移，可随地表径流迁移并在低洼汇集。因此，Rb/Sr比值可用于指示流域化学风化强度，比值越高，反映流域化学风化强度越弱，降雨量减少、气候相对干旱[54-55]。升温条件下Mg更易沉淀，因此在干旱区，常用沉积物中的Mg/Ca比值指示冷暖变化[56]，比值较高，气候相对干旱，反之亦然[57-58]。沉积物中Zr/Sr或Ti/Sr的变化主要取决于Sr的丢失程度[59]，Ti或Zr元素性质稳定，常赋存于矿物中，属惰性元素，而Sr易在低洼聚集，使Zr/Sr或Ti/Sr比值降低。因此，Zr/Sr或Ti/Sr比值可能指示了雨水淋溶程度，即降雨量大小[60]。降雨量增多、气候相对湿润时，Zr/Sr、Ti/Sr比值较低，反之亦然[60-61]。水介质中Ca^{2+}的碳酸盐或硫酸盐溶解度相对较低，沉淀析出在早期阶段，而Sr的盐类溶解度相对较高，一般在Ca^{2+}沉淀之后继续浓缩析出，故Sr/Ca比值可以反映气候变化。Sr/Ca比值高时，蒸发强烈，气候相对干旱，区域有效湿度较低；Sr/Ca比值低时，蒸发减弱，气候相对湿润，区域有效湿度较高[62-63]。

3.2 温泉湿地全新世环境演变过程重建

依据Rb/Sr、Ti/Sr、Mg/Ca、Zr/Sr、Sr/Ca 5种地球化学元素比值的气候环境指示意义及变化特征(图3)，结合^{14}C测年，将WQ-1岩芯所记录的全新世以来古气候环境演化划分为5个阶段：

(1) 第一阶段：暖干气候期(126.75~112.75 cm，10300—7700 cal a BP)

在此期间，5种元素比值在整个剖面最高且相对稳定，表明温泉湿地在该时期内气温较高，降雨量较少。这种水热条件下，流域内风化强度较弱，

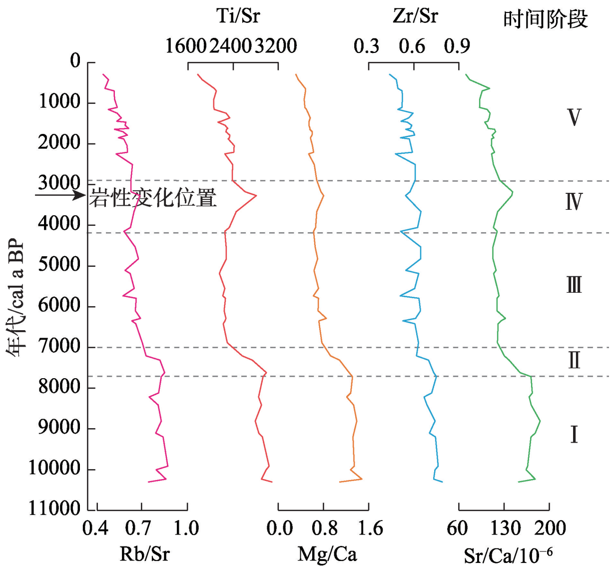


图3　温泉湿地WQ-1岩芯化学元素比值变化趋势

Fig. 3　Change trend graph of chemical element ratio in WQ-1 core section of Wenquan wetland

Sr、Ca输入减少，引起Rb/Sr、Ti/Sr、Zr/Sr比值升高。同时，较高气温，有利于Mg沉淀，Sr的盐类溶解度相对Ca^{2+}较高，故导致Mg/Ca、Sr/Ca比值升高。

（2）第二阶段：暖干到温湿的过渡期（112.75~109.00 cm，7700—7000 cal a BP）

此期间内，5种元素比值快速下降，可能指示了气温快速降低，降雨量明显增加，气候较上一阶段适宜。该时期水热条件有利于化学风化的进行，流域内风化强度明显增强，水动力增大，Sr、Ca汇入量增加，促使Rb/Sr、Ti/Sr、Zr/Sr比值明显降低。同时，由于气温降低，Mg沉淀减少，Sr相对Ca沉淀减少，使得Mg/Ca、Sr/Ca比值降低。

（3）第三阶段：温湿气候期（109.00~89.25 cm，7000—4200 cal a BP）

该时期，5种元素比值表现为“两峰夹一谷”，比值略降，表明气温持续降低，降雨量有所增加，风化强度进一步增强。地表径流进一步增加，促进Sr、Ca累积，使得Rb/Sr、Ti/Sr、Zr/Sr比值降低；气温持续降低，导致Mg/Ca、Sr/Ca比值的降低。

（4）第四阶段：温干气候期（89.25~83.25 cm，4200—2900 cal a BP）

这一时期，5种元素比值升高，表明研究区气温上升，降雨量减少，风化强度减弱，水动力减小，Sr、Ca输入量减少，引起Rb/Sr、Ti/Sr、Zr/Sr比值增大；气温的升高导致Mg/Ca、Sr/Ca比值增大。Ti/Sr、Sr/Ca、Mg/Ca 3种比值在3300 cal a BP前后出现峰值，指示可能存在干旱事件。

（5）第五阶段：冷湿气候期（83.25~50.25 cm，2900—81 cal a BP）

全新世晚期，5种元素比值持续降低并达到最低值，表明温泉湿地在晚全新世时期气温持续降低，降雨量持续增加，风化强度逐步增强。降雨的增加，径流输入增多，Sr、Ca输入量增加，导致Rb/Sr、Ti/Sr、Zr/Sr比值逐步降低；气温持续降低引起Mg/Ca、Sr/Ca比值的降低。

3.3　区域气候记录对比分析

本文基于沉积物化学元素比值，重建了研究区全新世以来气候演变过程，揭示了新疆地区全新世早期温干、中晚期逐渐湿润的气候演替类型。这种气候模式与新疆地区的其他替代性指标所指示的全新世气候特征具有较高一致性[20,26,35-45,64]。

（1）第一阶段（126.75~112.75 cm，10300—7700 cal a BP）

10300—7700 cal a BP期间，温泉湿地5种元素比值反映区域蒸发强烈、高温干旱、有效湿度低等气候特征在邻近区域有迹可循，如乌伦古湖（图4f）在10000—7000 cal a BP时期出现明显湖退[20]，艾比湖[35]（图4g）和博斯腾湖[41]在早全新世时期为沼泽或风沙沉积，赛里木湖[36]（6000 cal a BP之前）和巴里坤湖[44]（7800 cal a BP之前）A/C值较低（图4h、k）。

（2）第二阶段（112.75~109.00 cm，7700—7000 cal a BP）

7700—7000 cal a BP期间，温泉湿地5种元素比值指示区域有效湿度快速增加，气温快速降低，可能是对8.2 ka全球冷期气候事件的响应[65]，这在新疆的其他全新世记录中也有所体现。如8170—7630 cal a BP前后乌伦古湖介形类稳定同位素反映的冷湿环境事件[17]；8250—7900 cal a BP时期，艾比湖指示的强烈冷湿事件[66]。此外，Gun Nuur湖[67]、岱海[68]也记录了气候由暖干快速向冷湿的转变。由图4可知，早全新世后，新疆地区大范围有效湿度增加，众多湖泊开始发育形成[20,35,41]。

（3）第三阶段（109.00~89.25 cm，7000—4200 cal a BP）

5种元素比值反映7000—4200 cal a BP期间区域气候温湿，这可能是温泉湿地全新世气候最适宜期。类似的，赛里木湖6500—3500 cal a BP期间气

候温湿[36](图4h)；艾比湖[35]、乌伦古湖[20]湿度自7000 cal a BP以来渐增(图4g、f)；巴里坤湖7800—4300 cal a BP期间A/C值较高，也指示有效湿度较高[44](图4k)。鹿角湾[37]、柴窝堡湖[39]、托勒库勒湖[45](图4i~j、l)均指示中全新世期间气候较湿润。

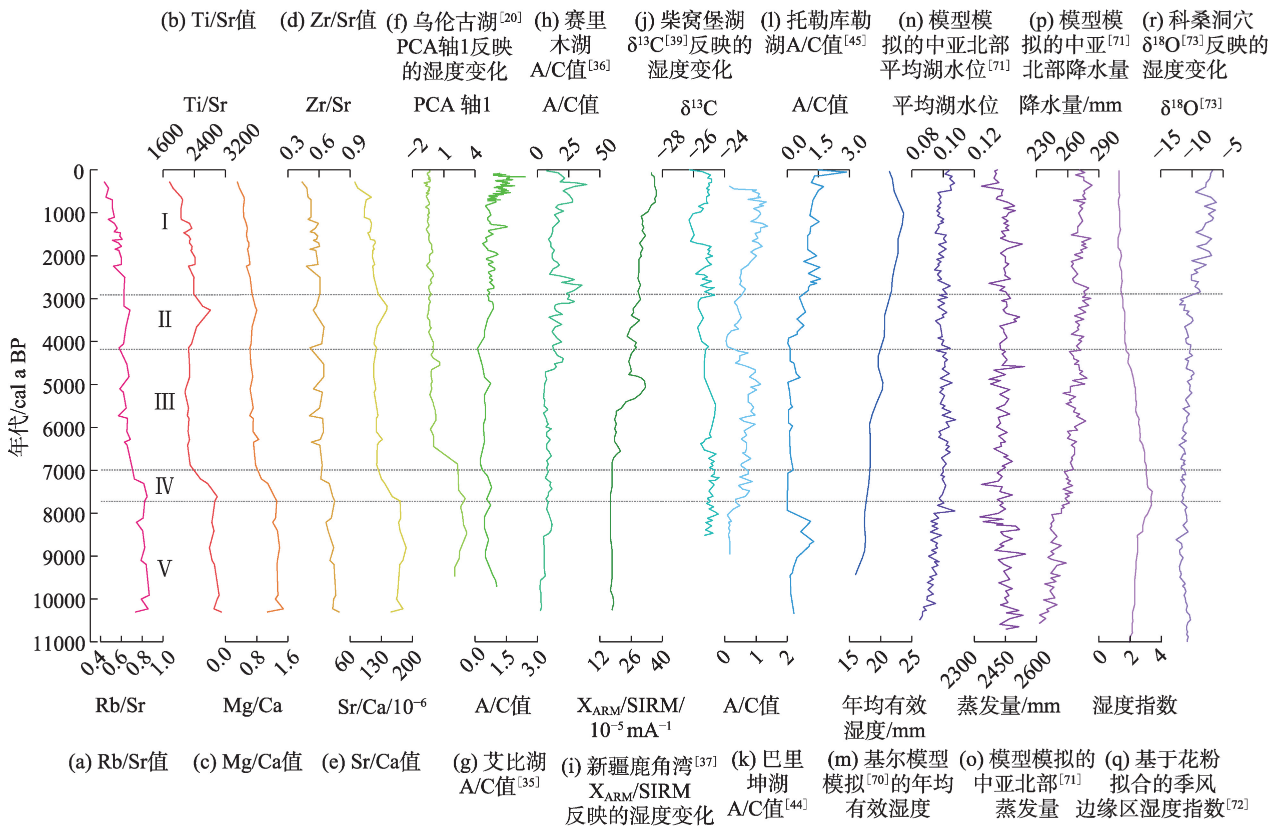
（4）第四阶段（89.25~83.25 cm，4200—2900 cal a BP）

然而4200—2900 cal a BP期间，温泉湿地5种元素比值反相变化，在3300 cal a BP时达峰值，指示可能出现高温干旱事件，这可能与敦德冰芯指示的3.0—2.9 ka BP的全新世次高温事件相关[69]。同样，赛里木湖[36]、巴里坤湖[44]的A/C值分别反映3500—2000 cal a BP和4300—2300 cal a BP期间气候相对干旱(图4h、k)；柴窝堡湖泥炭纤维素的$\delta^{13}C$值在3000—2800 cal a BP期间突然降低，也表明发生高温事件[39](图4j)。

（5）第五阶段(83.25~50.25 cm，2900—81 cal a BP)

2900 cal a BP以后，5种元素比值降低，并达全新世最低值，反映区域有效湿度较高，气温较低。晚全新世时期，艾比湖[35]、赛里木湖[36]、巴里坤湖[44]、托勒库勒湖[45]的A/C值增加(图4g~h、k~l)，新疆鹿角湾黄土-古土壤[41]的X_{ARM}/SIRM(10^{-5} mA^{-1})渐增(图4i)，柴窝堡湖$\delta^{13}C$值降低[39](图4j)，均指示晚全新世气候湿润；乌伦古湖[20]、玛纳斯湖[42]同样支持该结论。

新疆地区全新世逐渐湿润的趋势，也得到气候模拟数据支持。如基尔气候模型模拟的全新世中亚干旱区(40°~55°N，70°~97.5°E)年均有效湿度表明，10000—1200 cal a BP期间，湿度波动上升[70](图4m)。中亚北部平均湖水位、区域平均蒸发量和降水量的模拟结果表明，区域全新世降水量和平均湖水位均有明显上升，蒸发量则小幅下降[71](图4n~p)。然而，温泉湿地的湿度变化与东亚季风区湿度变化在时间上呈反相位变化。如东亚季风边缘区湿度重建结果表明，全新世早期逐渐湿润，中晚期湿度明显降低[72](图4q)。Cheng等[73]认为，暖期夏季太阳辐射高时石笋$\delta^{18}O$处于低值，可能是亚



注：A/C为蒿属/藜科；X_{ARM}/SIRM为非磁滞剩磁/饱和等温剩磁。

图4 其他代用指标记录的新疆全新世湿度变化对比

Fig. 4 Holocene humidity changes in Xinjiang recorded by other proxy indicators

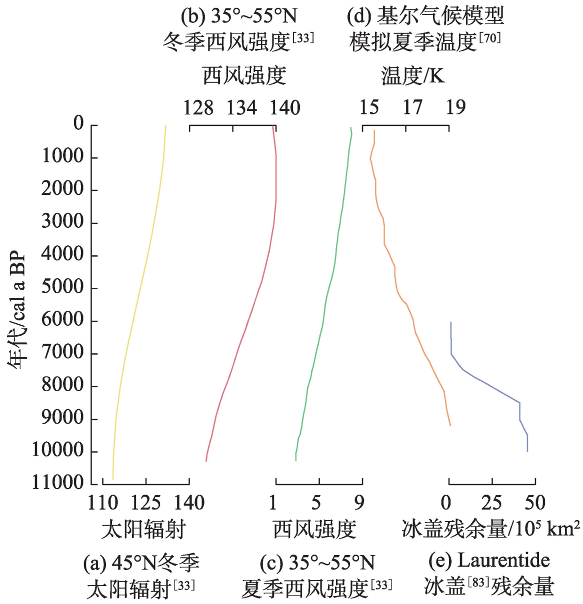
洲季风直接或间接影响所致(图4r)。

4　讨论

有研究认为夏季风可能在中全新世时期深入到新疆地区[74]，而Ran等[75]整理了新疆地区几个气候替代性指标记录，结果表明新疆地区仍以西风模式为主。温泉湿地5种化学元素比值表明全新世早期暖干，中晚期逐渐冷湿，这一气候演变过程与Wang等[26]、Zhang等[27]的研究相吻合，即类似于西风模式，而与典型季风气候区、东亚季风气候边缘区湿度变化异相。此外，沉积环境在4200—2900 cal a BP时期出现粉土/泥炭转换，而泥炭形成与累积有赖于稳定充足水源补给[76]。这可能是7700 cal a BP以来气温有所回升，高山冰川融水补充水源，促进植被生长，为泥炭层形成累积丰富有机物，3300 cal a BP前后高温干旱事件过后气候转温湿，水源补给充足，前期大量生长植物在淹水条件下，泥炭快速累积。因此，泥炭层的形成也印证了温泉湿地逐步湿润的趋势。

对新疆全新世气候变化机制研究表明气候湿润变化可能与冬季太阳辐射强度和冬季温度上升有关[26,75]。由于北半球冬季太阳辐射强度自全新世以来逐步增强，中、高纬地区增速差异，造成中高纬地区早全新世太阳辐射梯度增大，进而导致温度梯度增大，西风强度增强[37,77-78]。同时，里海、黑海、地中海等地蒸发量增加，更多水汽进入西风系统，为新疆地区带来更多水分[35,78]。数值模拟下冬季西风强度的增强也增加了上游水汽的蒸发和输送[79]。因此冬季降雪量增加促进天山山系冰进，冰川作为天山地区水资源重要组成部分，在高温干旱的暖期提供更多冰川融水，使得流域变得更加湿润，有效水分增加[80-82]。

此外，西北干旱区的有效湿度是降水量、蒸发量和温度季节变化相互作用的结果[36,70]。早全新世时期，北半球夏季温度相对较高，副热带高压北移，导致西北干旱区相对干旱少雨，全新世中晚期，副热带高压带逐步南移，对西北干旱区影响减弱，间接增加区内降水[37,78]。早全新世时期，北半球较高夏季温度使高纬地区更多冰川融水进入北大西洋，导致海表温度降低，蒸发减弱，西风系统水汽较少，使得新疆地区较干旱；中全新世后，进入北大西洋的冰川融水减少，蒸发加强，更多水汽进入西风系统使得新疆地区逐渐湿润[25,78]。同时，全新世以来夏季太阳辐射降低，新疆地区蒸发减弱，有效湿度增加[70]。温泉湿地全新世气候变化与邻近地区在气候转湿润时间及最适气候期略有差异，但整体变化趋势上相似。这种一致性表明，太阳辐射是区域温度变化的主要驱动因素，而温度变化对区域湿度变化的影响是显著的[36]。故温泉湿地的气候变化原因与邻近区域相似，可能与温度降低和降水的增加相关[50](图5)。



注：西风强度以太阳辐射强度梯度表示。

图5　西风区湿度变化可能驱动机制

Fig. 5　Possible forcing mechanisms of Holocene moisture evolution in the westerly area

5　结论

(1) 温泉湿地沉积物化学元素比值变化表明，自10300 cal a BP以来，新疆地区气候环境经历了暖干(10300—7700 cal a BP)-暖干至温湿的过渡期(7700—7000 cal a BP)-温湿(7000—4200 cal a BP)-温干(4200—2900 cal a BP)-冷湿(2900 cal a BP以来)的变化过程。

(2) 温泉湿地气候演变与赛里木湖、艾比湖、乌伦古湖、巴里坤湖等湖泊记录的气候环境变化相吻合，验证了新疆地区的水热组合为暖(冷)干(湿)模式，即类似于西风模式。

(3) 7700—7000 cal a BP时期指示的降温事件，可能是8200 cal a BP全球变冷事件的响应；4200—2900 cal a BP时期指示的升温事件也可能与敦德冰芯指示的3000—2900 cal a BP的全新世次高温事件相关。与邻近地区其他替代指标对比发现，新疆地区逐渐湿润趋势可能是全新世温度降低与降水增加共同决定。

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Holocene sediment element geochemical records and their paleoenvironmental significance in Wenquan area of western Tianshan Mountains

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Abstract: Climate change during the Holocene epoch in the arid Central Asia (ACA) has been one of the research hotspots in paleoclimate and global change research communities. Compared with the Asian monsoon region, the history of the change in humidity and the combination of moisture-temperature in the ACA region in the Holocene epoch are still controversial. In this study, we present the results of sediment element geochemical records taken from the Wenquan wetland of western Tianshan Mountains in Xinjiang, China. The core was collected in September 2017 using a Russian peat corer. The dated AMS ^{14}C ages were calibrated to calendar years before present using the IntCall3 calibration dataset. Concentrations of Rb, Ti, Sr, Zr, Mg, and Ca were determined using an inductively coupled plasma atomic emission spectrometer, and the error of parallel analysis was $<\pm5\%$. Holocene environmental evolution was reconstructed using the Rb/Sr, Sr/Ca, Ti/Sr, Mg/Ca, and Zr/Sr chemical element ratios. Through comprehensive analysis of the climatic and environmental indicators of the five ratios, and contrastive analysis with adjacent areas, this paper provides a useful information for a better understanding of the Holocene moisture-temperature relationship, and to identify patterns that drove the Holocene climate change in the Wenquan wetland. The results show that the Wenquan wetland is able to provide a reliable record of the Holocene climate change in Xinjiang. Based on analyses of the chronology records, the five element ratios reveal that the climate of the Wenquan wetland region during the last 10300 cal a BP has experienced a warm dry period (10300−7700 cal a BP), a warm dry period to warm wet period (7700−7000 cal a BP), a warm wet period (7000−4200 cal a BP), a warm dry period (4200−2900 cal a BP), and a cold and wet period (2900−81 cal a BP). This process is consistent with the climate change records and model simulations of neighboring regions, which verifies the warm/dry and cold/wet climate change patterns in Xinjiang during the Holocene. This indicates that the climate environment change in Xinjiang is similar to the westerly domination pattern and exhibits an "out-of-phase" relationship with the pattern of monsoonal evolution in eastern monsoonal Asia. Moreover, the cooling process indicated by the ratio of the core elements in the Wenquan wetland sediments during 7700−7000 cal a BP may correspond to the global cooling event of 8.2 cal ka BP. The warming process observed during 4200−2900 cal a BP may be consistent with a Holocene sub-high-temperature event reflected by Dunde ice cores from 3.0 to 2.9 cal ka BP. In recent years, an increasing number of researches has concentrated on ACA region moisture changes and the possible mechanisms responsible for these changes, based on a westerly dominated regime. Compared with other proxy indexes in the surrounding region, it was found that the trend of gradual wetting in Xinjiang may be the result of the combined effect of decreasing temperature and increasing precipitation in the Holocene.

Key words: wetland; element ratio; Holocene; climatic environment; regional comparison; Xinjiang